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INVESTIGATING UHF TELEMETRY FOR ELECTROMAGNETIC LAUNCHERS

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This paper describes an experimental investigation of the feasibility of microwave telemetry for conveying diagnostic information collected during and after launch from an electromagnetic (EM) gun. The study focused on extending the Hardened Subminiature Telemetry Sensor Systems (HSTSS) technology for use in EM launch environments. While HSTSS technology has already been successfully demonstrated in high-g, high-pressure launch environments in conventional gun systems, it has not yet been tested in an EM gun environment, where the launch accelerations are generally higher and where the projectile can be exposed to high magnetic fields and EM transients. In this work, ultra high frequency (UHF) telemetry measurements were made at fixed locations in the magnetized bore of the Medium Caliber Launcher (MCL) at the IAT to assess the effect of the EM environment on telemetry and the HSTSS-like components. The data show that UHF FM signals can both propagate and be received in this non-optimal environment. Signals were received with minimal loss after propagating along the entire bore as well as through the containment wall. To examine the effect of high, transient magnetic fields on HSTSS-like components, the telemetry package was located both ahead of and behind a stationary armature, with the latter case simulating the higher fields in an EM launch with a muzzle shunt. The results showed that, in an EM launch without a muzzle shunt, the telemetry package could be positioned far enough ahead of the armature such that there would be no interference in the received telemetry signals. However, when a muzzle shunt was simulated, there were momentary disruptions in the transmitted signal coincident with fast rising, transient magnetic fields. The use of a thick metallic cylindrical shield surrounding the telemetry components reduced the induced voltages due to transient magnetic fields somewhat and slightly improved the observed telemetry signal.

INTRODUCTION

To aid in the research and development of projectiles for EM gun systems, there is a need for on-board instrumentation. Both in-bore and free flight phenomenon must be measured and understood. Parameters such as, but not limited to, setback acceleration, balloting, pressure, yaw/pitch rate, and spin need characterization. For smart munitions, on-board diagnostics may also be needed to monitor the performance of seeker or inertial measurement unit sensors. On conventional gun systems this information is routinely gathered using an on-board telemetry system. Until recently these telemetry systems have been expensive and limited to large caliber projectiles. However, under the U.S. Army's Hardened Subminiature Telemetry and Sensor

System (HSTSS) program a new family of rugged, low cost telemetry components is being developed.

The HSTSS program, a tri-service program scheduled to complete all development contracts in FY03, is currently developing state-of-the-art telemetry components and subsystems for missile and ballistic applications. The goal of the program is to provide lower cost, user configurable telemetry components for making in-flight measurements of standard and smart munitions. Products being developed include a transmitter chip set, a data acquisition chip set, a reference oscillator, power sources, various sensors, and electronic packaging techniques for the ballistic environment. All of the devices are available in their lowest form of packaging (e.g., integrated circuit die) and are being designed to survive setback accelerations greater than 100,000 G's. To date, the program has fielded telemetry systems for the Multiple Launch Rocket System (MLRS), Advanced Kinetic Energy Projectile Program, and the DERA ETC gun programs. HSTSS is now being considered for electromagnetic launchers (EML) to provide on-board diagnostics for an EM launched projectile [1].

Unlike conventional gun systems, EM gun systems have the added complexity of high, transient electric and magnetic fields during the launch phase that may affect the performance of the on-board electronic systems, particularly the RF link. There are at least two additional considerations for wireless telemetry when it is used as an on-board diagnostic on an EML, such as the Medium-Caliber Launcher (MCL). The dimensions of the MCL bore and containment structures are approximately those of a rectangular waveguide having a 3.75 GHz cutoff for the lowest-order propagating mode - significantly higher than the carrier frequency (2.2 GHz) used in the HSTSS. It will be determined whether microwave energy can propagate inside as well as through the MCL bore structure, which is also effectively closed on one end by a conducting armature. Secondly, during any EM launch there is significant transient magnetic field - which may render the on-board electronics at least temporarily inoperable. For some configurations of the MCL, for example, such fields reach 10's of T at a rate 10's of T/ms in regions where HSTSS electronics would be located.

The objective of this study is to evaluate the feasibility of using an on-board telemetry system in this harsh environment. A series of stationary tests were conducted using a very simple analog RF link to (1) determine limitations in transmission through the EM launcher and containment structures, and (2) characterize the performance of the telemetry link during and just after the application of high magnetic field transients. The remainder of this paper reviews the test methodology, describes the telemetry module, and summarizes the results.

PRELIMINARY STUDIES

Quiescent Railgun Environment

The high currents in a railgun result in large transverse forces on the rails that must be resisted by an external containment structure. The MCL uses a close-fitting structure composed of insulated metal laminations, as shown in Fig 1. The laminations allow a change in the magnetic field to propagate into the lamination gap at the speed of light while diffusing into steel laminations on the order of 2-μs [2]. Thus, on the time-scales associated with EM launch dynamics (> 20-μs), the containment structure is essentially transparent to the transverse field. However, the close proximity of the rails and laminated-steel containment form a complicated, difficult-to-analyze UHF telemetry environment, and accurate estimation of the UHF energy propagating through the containment is an expensive calculation.

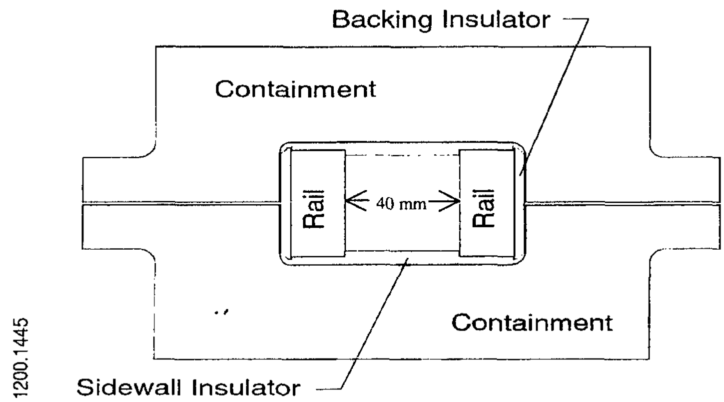

FIGURE 1. Cross-section of the Medium Caliber Launcher is shown viewed down the barrel. The parts marked 'containment' are made of stacks of 1.5-mm thick steel laminations.

In Ref [3], a simple experimental investigation on the MCL demonstrated that UHF signals will both propagate and be detected in a quiescent EM launcher environment. Those measurements were conducted using a continuous wave UHF transmitter and a spectrum analyzer each connected to a dipole antenna, positioned inside and/or outside of the MCL bore. In that study, neither the transmitter nor the receiver were exposed to EM railgun transients; nor were the measurements conducted in the presence of an armature, where the effect of the MCL, acting as a waveguide that is closed on one end, could be investigated. Nevertheless, the results indicated that the effect of the MCL rails and laminated containment structure was minimal. The reduction in the received UHF signal level was only about 5-10 dB over the length of the 10-m barrel compared to that of equidistant out-of-bore measurements, regardless of the receiving antenna position. Thus, in Ref [3], no fundamental roadblocks associated with the railgun and containment structure were identified.

Magnetized Railgun Environment

An equally important concern is the effect of the applied transient magnetic field on the telemetry link. In typical MCL experiments, 200-300 g launch packages are accelerated up to 2500 m/s over the first few meters of a 7-m long launcher. The driving current rises to about 1.0 MA peak in about 500 ms, persists at a plateau for a few milliseconds, and then decays to several hundred kilo-Amp by the time the launch package leaves the gun. The schematic in Fig 2 shows the rails, the armature, driving current and magnetic field lines that are perpendicular to the current flow. The bore geometry used in this study was 1.575x1.575 in (40 x 40 mm) in cross-section and 50-in long. The rails, which were made of 6061-T6 Aluminum (¾-in x 1¾-in cross-section), were separated by a 6061-T6 Aluminum block (1¾-in in height and 1-in in axial extension) acting as a stationary armature. The schematic in Fig 3 shows the basic experimental configurations used in the present study.

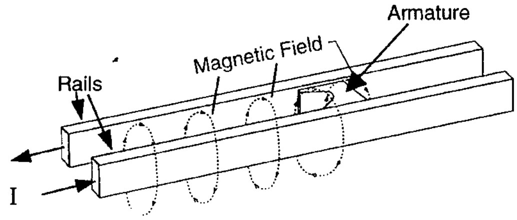

FIGURE 2. A schematic diagram is shown of the armature and rails of the Medium Caliber Launcher (containment not shown). At the bore center, magnetic field lines are perpendicular to the bore axis.

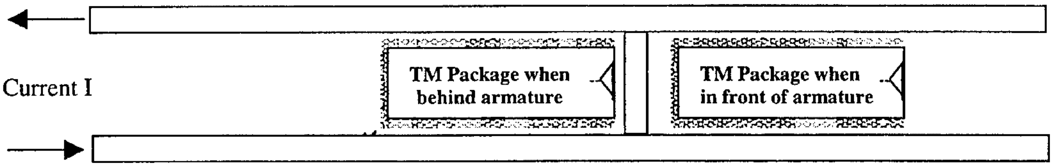

FIGURE 3. Shown is a schematic diagram of the fixed Aluminum armature and Aluminum rails used to assess the magnetic fields that would be exposed to the telemetry system The magnetic containment (not shown) is also present. The locations of telemetry transmitter package are shown at two locations tested in the telemetry experiments. Metal, cylindrical magnetic shields surrounding the package and used in several of the tests are indicated by the "▓" pattern.

When a projectile is launched with a railgun, the voltage induced on electronic components on board is the result of two terms: one proportional to the rate of change of magnetic flux and the other proportional to the projectile velocity. While field measurements associated with a stationary armature offer only a limited approximation of comparable dynamic railgun fields, they were determined in Ref. [4] to provide an order of magnitude estimate of the magnetic flux density (**B**) and the induced voltage, which is proportional to d**B**/dt. Figs 4 and 5 show the applied current waveforms, and the peak magnetic flux densities along the bore centerline, respectively. At locations behind the stationary armature, the peak value of |**B**| was 1.6 T and the peak value of |d**B**/dt| was 6 T/ms. As expected, except in the vicinity of the armature, the magnitude of the magnetic field was essentially independent of axial position and directly proportional to the peak current level at 16 T/MA. At locations ahead of the armature, **B** was markedly reduced. The peak in **B** was nearly an order of magnitude lower at 1.5-2 armature heights ahead of the trailing edge of the armature, and was more than two orders of magnitude lower at 4.5-5 armature heights, as illustrated in Fig 5.

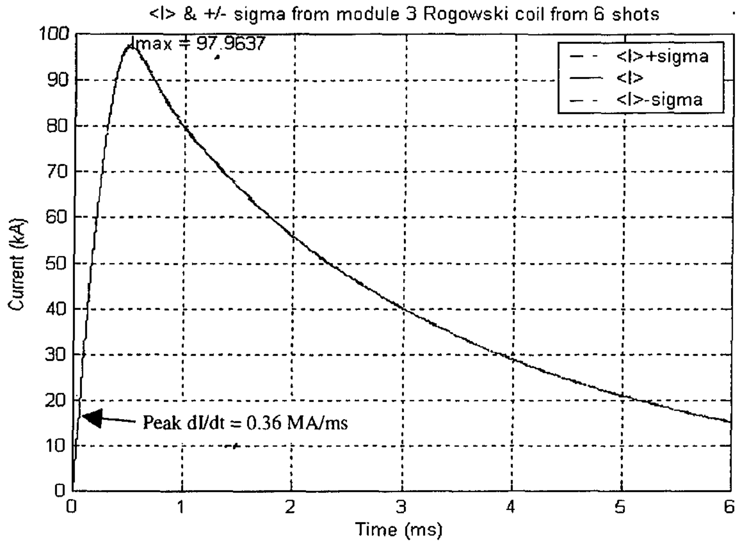

FIGURE 4. Measured railgun current waveforms from Ref. [4] are shown that were used to obtain measurements of the stationary magnetic flux density **B** in the bore center. For a 100 kA peak current, the peak current growth rate was 0.36 MA/ms. The corresponding peak in **B** was 1.6 T, normal to the bore axis, and the peak value of **dB**/dt was 16 T/MA × 0.36 MA/ms = 6 T/ms.

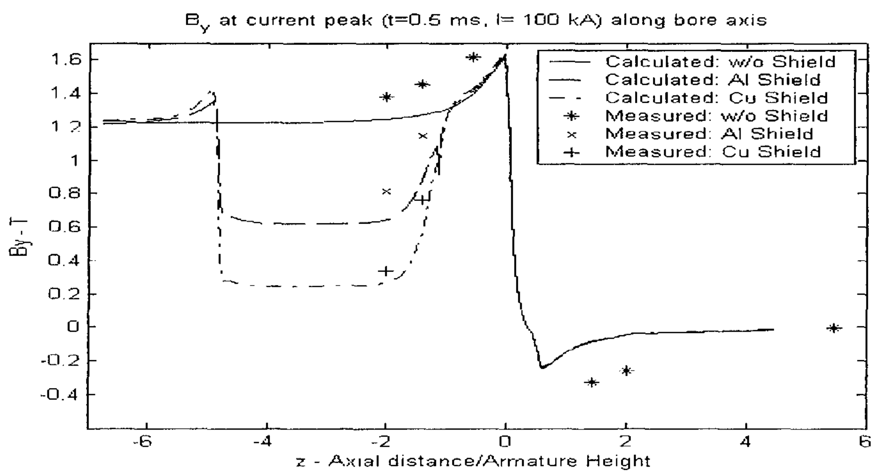

FIGURE 5. Measurements and EMAP3D calculations of the magnetic flux density were made for three different shield cases, which occupied a region 1-5 armature heights behind the trailing edge of the armature [4]. The peak component (perpendicular to bore axis) of **B** is shown during the current peak.

In a railgun launch, if the armature current is not zero at exit, an electrical arc will form as the armature leaves the gun and may cause a number of undesirable consequences, most of which can be alleviated with the use of a muzzle shunt [5]. Unfortunately, when a muzzle shunt is employed, significantly larger EM transients will develop ahead of the armature as the magnetic flux is compressed between the armature and the muzzle shunt. The magnetic field transients induced because of a muzzle shunt are difficult to measure or calculate accurately. However, the muzzle voltage, normally 10-30 V on the MCL, has been measured in kilovolt ranges when such a shunt is attached [6]. Thus, the use of a muzzle shunt in an EM launcher may subject the launch package to extremely high voltage transients and have dire consequences for the on-board instrumentation in the telemetry package.

One potential solution is the use of a magnetic shield. The ability of a hollow, metallic cylinder to mitigate the effects of the high, transient EM field was also explored in Ref [4]. Two hollow, 6½-in long, 1/10-in thick cylindrical shields, closed on one end, were tested. One was made of Al7075 and weighed 130 g, the other was made of ETP Cu and weighed 430 g. As expected, the greatest reduction in the magnetically induced voltage was achieved by the more conductive and heavier copper shield. Compared to the case with no shield, the induced peak voltages were reduced by more than 80% during initial current rise (i.e., < 100 μs). However, after 250 μs, the induced fields were no longer attenuated by the shields. If necessary, improved shielding may be obtained with more sophisticated shield design; however, significant weight penalties could render the use of shields impractical. Nevertheless, their effect on telemetry was also investigated in this study.

TELEMETRY EXPERIMENTS

The telemetry experiments were conducted by placing the transmitter module inside the MCL bore and closed containment structure. The frequency modulated (FM), UHF signal was transmitted to two side-by-side receivers located outside the bore, and recorded digitally for subsequent analyses. In this section, the telemetry module and receivers are first described. Telemetry measurements - conducted in a full length, quiescent railgun environment in the presence of a conducting armature - are discussed next. Finally, telemetry in a magnetized railgun bore is examined. Here, the effect on the telemetry is investigated by analyzing the carrier frequency shift and the frequency spectrum of the received, modulated sub-carrier signal with changes in 1) antenna orientation, 2) telemetry transmitter module (TM) location, 3) **B** inside the bore, and 4) magnetic shielding.

Telemetry Transmitter and Receiver

The TM shown schematically in Fig 6 and photographed in Fig 7 was made up of boards and commercial components previously used in other telemetry systems. The module, powered by a regulated, 10-cell 170mAh Ni-Cd battery, is an FM/FM system that was used without modulating the sub-carrier oscillator (SCO). The SCO is a 225-kHz ± 15% voltage-controlled oscillator (QuadTron VCO) - used at its lower band-edge (~192 KHz). The signal was amplified before it was used to modulate the 2.2-GHz carrier produced by a second VCO made by Pacific Monolith (PMI VCO). This UHF signal was then amplified by a Celeritek power amplifier to produce about 17dBm (50 mW), and then fed by a probe to a 50-mil rectangular patch antenna. The dimensions of the antenna were nominally 860 mils by 1024 mils, with the feed point inset 331 mils for impedance matching. This module was entirely encapsulated in STYCAST insulating material with only the antenna and battery connector exposed. The encapsulated package and batteries were also enclosed by magnetic shields in some of the tests, as illustrated in Fig 3, above.

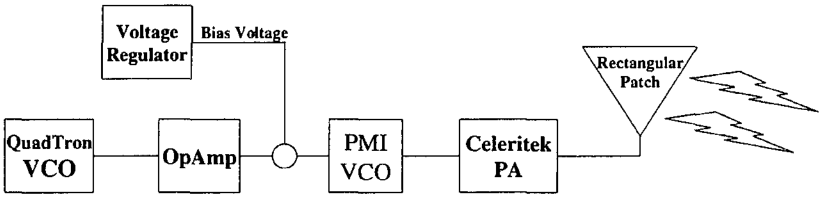

FIGURE 6. A schematic diagram of telemetry transmitter module tested in this analysis is shown.

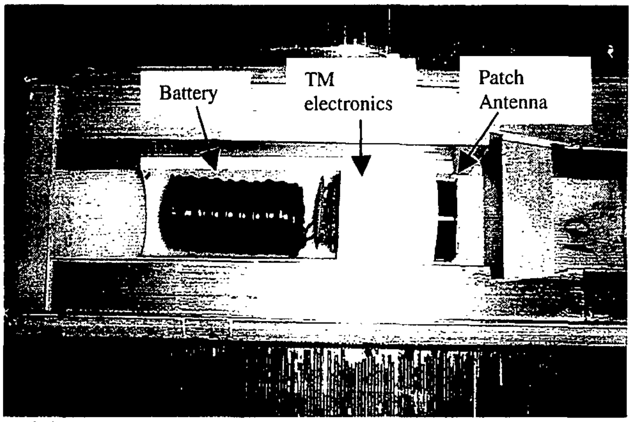

FIGURE 7. A photograph of the telemetry transmitter module tested behind the armature in this analysis is shown. With the upper sections of the containment-structure and magnetic shield removed, the TM package, armature and rails are visible.

Two similarly oriented receiving antennae were placed within a meter of each other, and positioned to detect the telemetry signal, as shown schematically in Fig 8. A spectrum analyzer connected to antenna 1 was used to establish the optimum positioning of both antennae by continuously providing the carrier noise levels of the received UHF signal. The receiver was used to demodulate the received signal, which was digitized and stored for subsequent analysis.

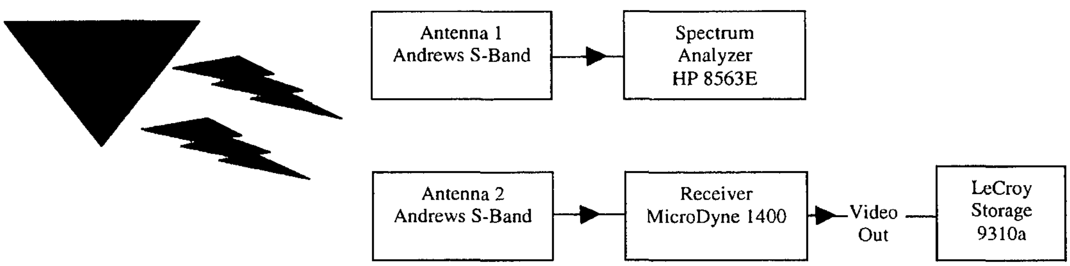

FIGURE 8. A schematic diagram of telemetry receiver tested in this analysis is shown. Signal and noise levels were measured with the spectrum analyzer to optimize positioning of both receiving antennae. Experimental measurements of the demodulated signal detected by the MicroDyne receiver were digitized and recorded by the LeCroy oscilloscope for analyses.

Telemetry Measurements in the Quiescent MCL

Experiments were first conducted under quiescent conditions to ascertain the interference effects of the rail and containment structure in the presence of a conducting armature, which effectively closed one end of the MCL "waveguide". Measurements corroborated those obtained in [3], and further established that signals transmitted from the telemetry package - placed in front of a conducting armature at positions throughout the full 7-m bore - were readily received and demodulated using receiving antennae positioned several feet outside the bore, anywhere from 50 to 345 inches from the transmitting antenna. Extremes in the signal/noise levels versus antennae separation were mild, varying only a few dB, and the MCL containment structure was observed to reduce the signal level by only about 10 dB.

Telemetry Measurements in a Magnetized Bore - TM Package ahead of the Armature

The reminder of the experimental analyses considered telemetry in a magnetized bore with the containment structure in place. The TM package was first placed in front of the armature (as illustrated in Fig 3), with the patch antenna at the muzzle end of the package at 4½ armature-heights from the armature's trailing edge - a relatively practical arrangement if it is to be launched with a standard KJ200 armature on the MCL without a muzzle shunt. The receiving antennae were positioned outside the bore and containment structure about 10-ft from the package. Telemetry measurements were recorded for a number of tests, with currents varying from 0 to 100 kA, and both with and without magnetic shields.

The SCO signals were analyzed by forming spectrogram plots. These were generated by sub-dividing each 10-s (250k) data record into 328-μs (8k) sub-records. The sub-records were 50% overlapped, with a Hamming window applied before calculating each digital Fourier transform (FFT). Every FFT had a 12.5 MHz Nyquist frequency and a 3-kHz fundamental frequency, but each plot was frequency limited to 500 kHz and amplitude limited to a minimum of -75 dB relative to the peak. The origin of the time axis corresponds to the beginning of each current pulse, where spectra at positive times describe the telemetry measurements just after the current pulse was applied.

The spectrograms corresponding to the conditional extremes investigated in front of the armature are shown in Fig 9, where the Aluminum shielded TM package was used and no current was applied to the railgun, and in Fig 10, where an unshielded TM package was used and 100 kA was applied. The received modulation signal peaked at 192.6 kHz in all of these cases, with the first harmonic clearly visible at 385 kHz, about 25 dB below the fundamental. No change or degradation was observed for any of the measurements in which the telemetry package was placed in front of the armature.

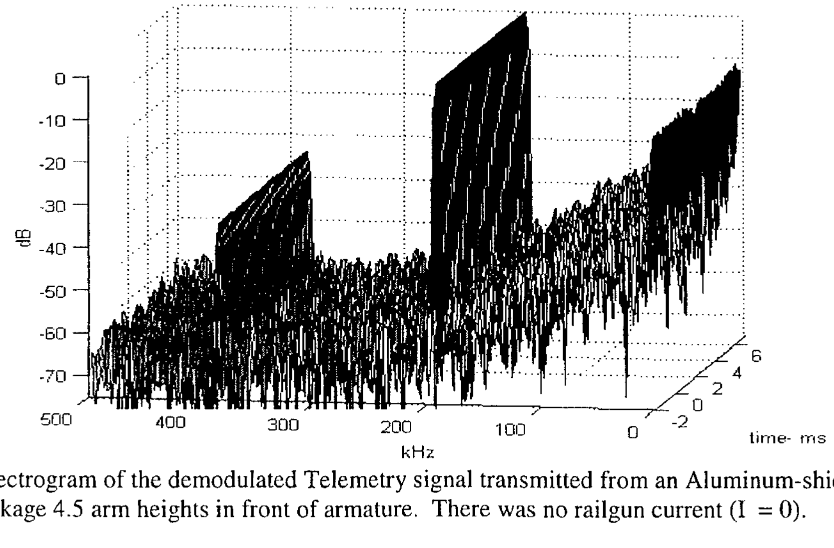

FIGURE 9. Spectrogram of the demodulated Telemetry signal transmitted from an Aluminum-shielded TM package 4.5 arm heights in front of armature. There was no railgun current (I = 0).

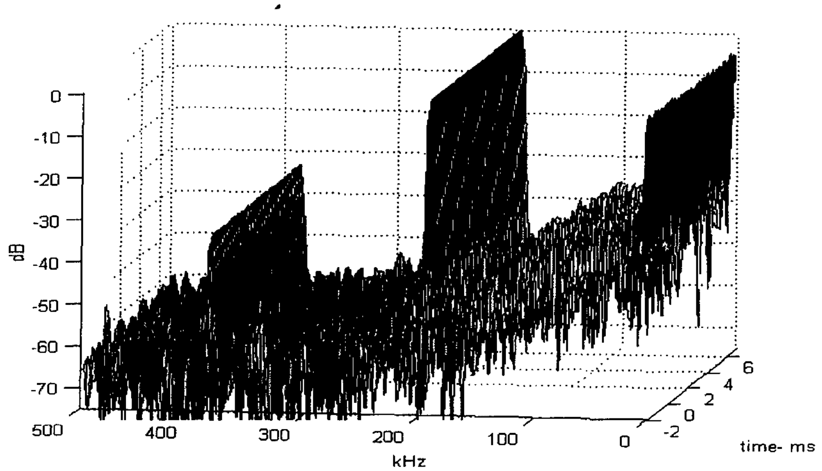

FIGURE 10. Spectrogram of the demodulated Telemetry signal transmitted from an unshielded TM package 4.5 arm heights in front of armature. The peak railgun current I was 100 kA.

Telemetry Measurements in a Magnetized Bore - TM Package behind the Armature

The magnetic field transients had to be increased significantly in order to affect changes in the received telemetry signal. This was accomplished by placing the TM package directly behind the armature, with the patch antenna at the muzzle end of the package, positioned 0.45 armature-heights behind the armature's trailing edge, as illustrated in Fig 3. For the same 100-kA railgun current, the magnetic fields and induced voltages in this region were more than 2-orders of magnitude higher than the corresponding fields and voltages in regions ahead of the armature, as discussed above.

When the telemetry module was exposed to these higher field transients, a dc shift in the receiver's video output was observed. Such a change occurs when there is a corresponding shift in the carrier frequency. Because of the FM modulation scheme used, any change in the transmit frequency corresponds to a voltage shift after demodulation. The amount of voltage shift on the output was controlled by the video gain of the receiver, which for these measurements was about 3 V/MHz. The intermediate frequency (IF) bandwidth of the receiver was set to allow it to frequency demodulate the UHF signal within a (locking) window of about ± 2 MHz.

The measured frequency shifts of the received signal are shown as a function of time in Fig 11 for three magnetic-shield examples when a 100 kA current pulse was applied. The origin of the time axis corresponds to the beginning of each current pulse. The frequency shift in the case without a shield was somewhat different from those in the other two cases. It had a sharp, positive frequency shift, which was coincident with the rise in magnetic field, and remained positive for times less than 0.3 ms. The frequency shift in the case with the copper shield was the smallest of all, but persisted for the longest time – consistent with the longer magnetic diffusion time associated with this more conductive shield.

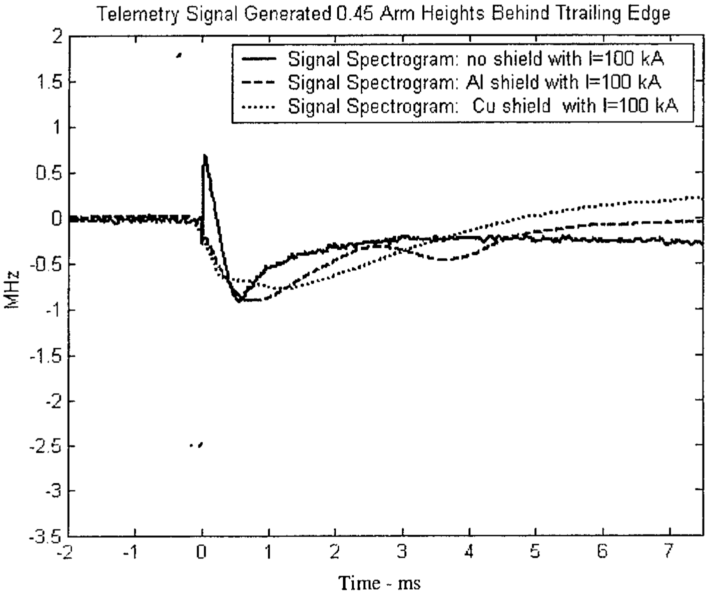

FIGURE 11. Measured (received) carrier frequency shifts, shown for different TM shields, were caused by magnetic field transients behind the armature.

More significant frequency shifting was observed when 1) the TM signal polarization was changed by rotating the patch antenna by 90° with respect to the rails, and/or 2) when |**B**| was increased by a factor of three by increasing railgun current. Two such examples are shown as a function of time in Fig 12, along with one of the previous cases, the 100-kA current, Aluminum shielded case with the original antenna orientation, for reference. In these two cases, the effects of the antenna rotation and/or the increase in |**B**| are so large that the telemetry link is lost temporarily.

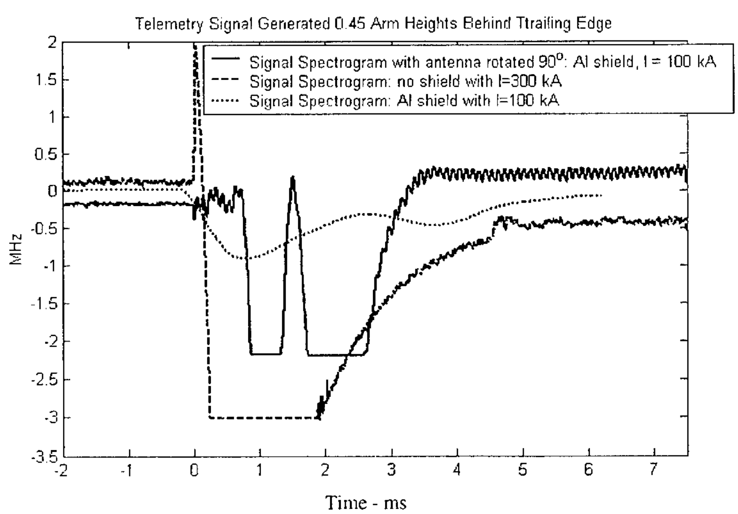

FIGURE 12. The measured (received) carrier frequency shifts become clipped if the TM antenna is rotated 90°, or if the current waveform shown in Fig 4 is increased by a factor of 3.

Spectrograms of the demodulated signal for the five high field transient cases corresponding to Figs 11 and 12 are shown in Figs 13-17. The results in Figs 13-15, which correspond to the cases having no shield, an Aluminum shield, and a Copper shield, respectively, show that the 192.5 kHz received modulation signal and its first harmonic had neither frequency nor amplitude deviation. Both were essentially unaffected by the high field transients - even as the carrier frequency was shifted by 1 MHz. Although a low-level broadband noise more than 50 dB below the received signal level emerged during the high magnetic field rise, only the lowest frequency components (< 20 kHz) were affected over the times during which the carrier frequency shifted (see also Fig 11). The results in Figs 16 and 17, which correspond to the cases where the TM antenna was rotated by 90°, and where |B| was increased by a factor of 3, respectively, show that the telemetry link was lost completely due to large frequency shifting (see also Fig 12). However, the modulated signal recovered in all cases - undistorted in both frequency and amplitude and coincident with the recapture of the telemetry link.

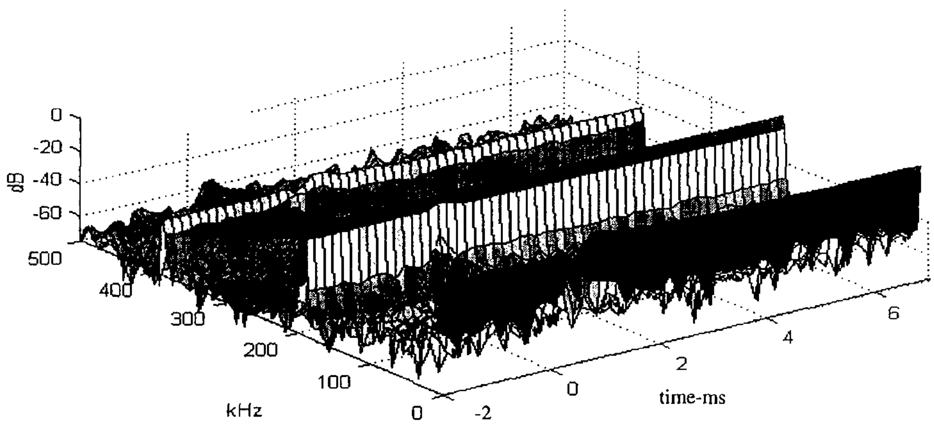

FIGURE 13. Spectrogram of the Received Signal with no magnetic shield, peak current I=100 kA.

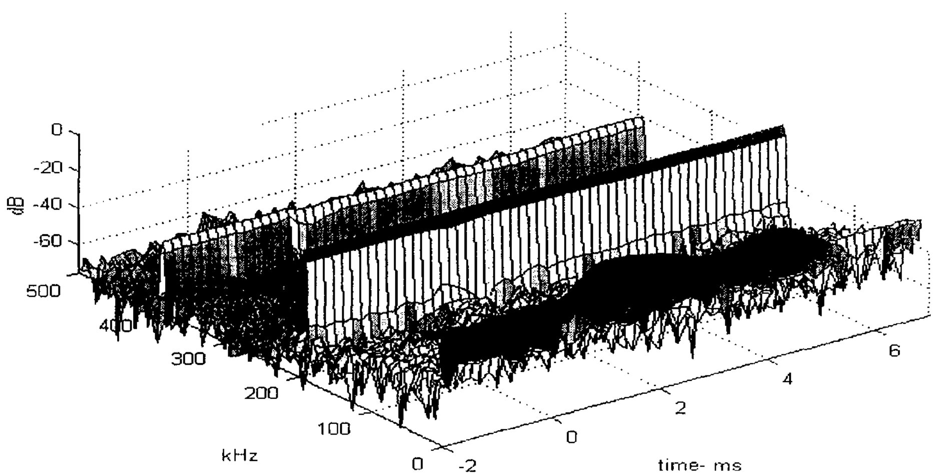

FIGURE 14. Spectrogram of the Received Signal with Al magnetic shield, peak current I=100 kA.

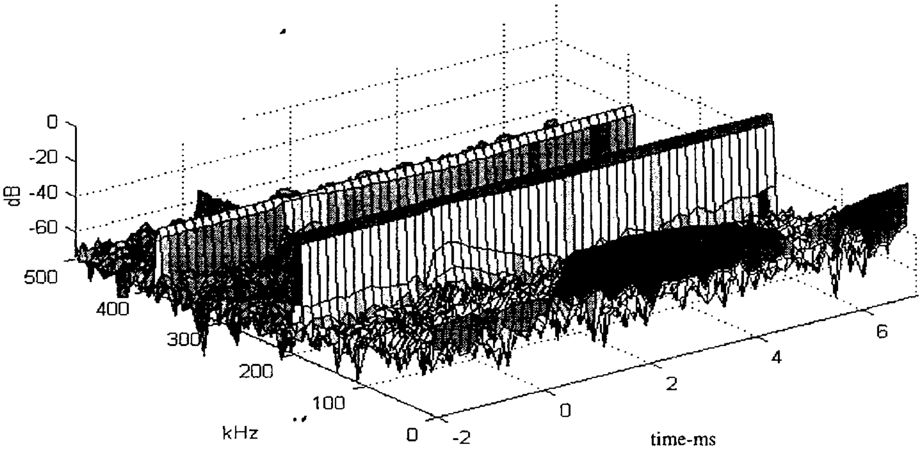

FIGURE 15. Spectrogram of the Received Signal with Cu magnetic shield, peak current I=100 kA.

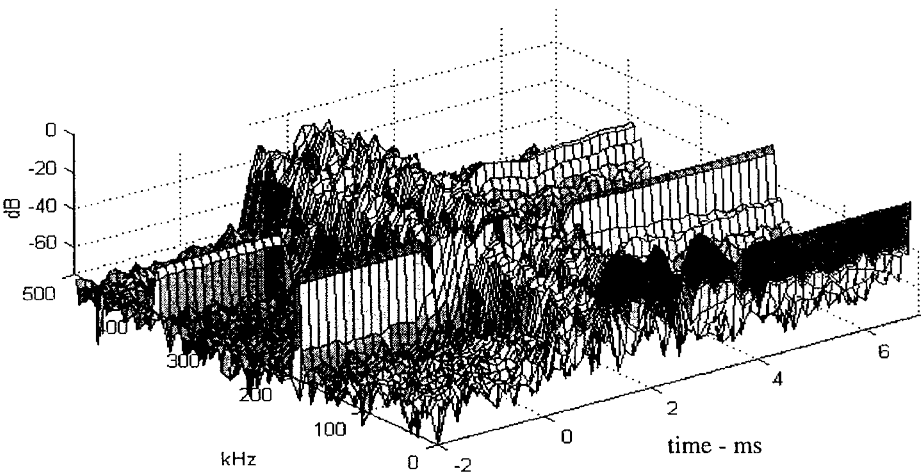

FIGURE 16. Spectrogram of the Received Signal with TM antenna rotated 90 deg, no magnetic shield.

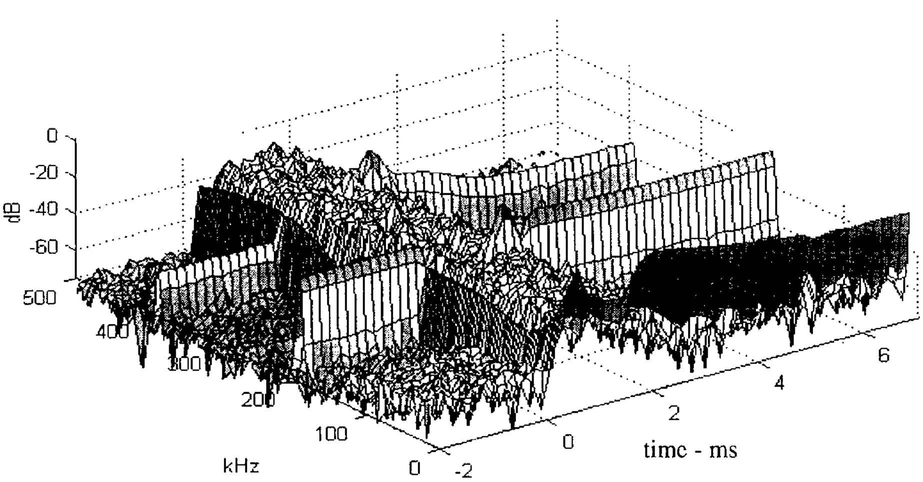

FIGURE 17. Spectrogram of the Received Signal with neither antenna rotation nor magnetic shield, peak current = 300 kA.

Discussion

Possible reasons for a frequency shift of the transmitter are 1) frequency pushing of the VCO due to a power supply fluctuation or 2) frequency pulling of the VCO because of an effective impedance change and/or induced voltage on the transmitting antenna. Loss of the telemetry link will occur whenever the telemetry signal experiences a frequency shift that is larger than the tuning bandwidth of the receiver or whenever there is a failure of the TM package. The telemetry link always recovered in this investigation. So, while it is conceivable that the TM package may have only suffered a transient failure each time the telemetry link was temporarily broken, it is more likely that the transmitter carrier frequency shifted outside the tuning bandwidth of the receiver causing loss of data.

For the two 100 kA cases in Fig 12 - where the test conditions were identical except for a 90° rotation of the TM antenna, the telemetry link temporarily broke only when the antenna was rotated. As the diagram in Fig 18 illustrates, the TM patch antenna is normally oriented to transmit the signal with the H plane aligned in quadrature to the strongest component of the railgun's magnetic field transient. This orientation minimizes coupling of the antenna with that field component; however, if it is rotated by 90°, coupling is maximized. Thus, the primary cause of the temporary loss of the telemetry link in this study can probably be attributed to coupling to the antenna of the large, transient B field.

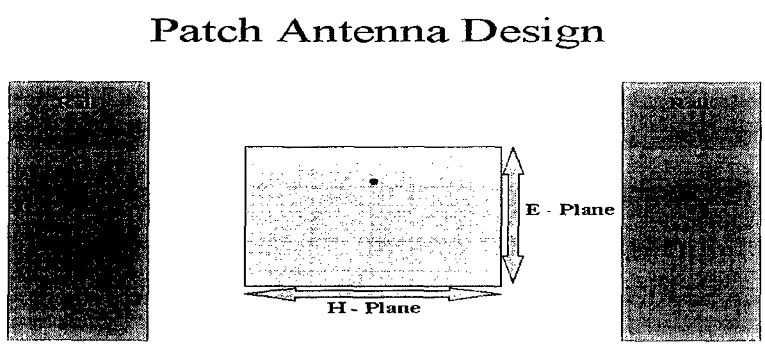

FIGURE 18. The telemetry signal polarization is shown - viewed into the railgun barrel - for the normal orientation of the patch antenna. The magnetic field from the railgun is strongest and aligned with the E-Plane at the barrel center. If the antenna is rotated 90°, the H-plane is aligned with the strongest magnetic component of the railgun.

SUMMARY AND CONCLUSIONS

An experimental investigation has been conducted to analyze the feasibility of using telemetry techniques in conjunction with on-board diagnostics for EM launchers. It was determined that microwave energy propagates without difficulty inside as well as through the MCL barrel, which is surrounded by a laminated containment and closed on one end by a conducting armature. The magnetic field transients associated with active EM launches were simulated in stationary experiments with magnetic fields in the bore increasing at rates as high as

17 T/ms up to peak levels of 4.8 T. Aluminum and copper cylinders surrounding the telemetry transmitter were also investigated to assess their effectiveness as magnetic shields.

The results of this study indicate that telemetry can likely be performed successfully in an EM launch - and should be evaluated further using the actual HSTSS components as they become available. There were two cases observed where telemetry failed after losing frequency lock of the signal: 1) when an inappropriate transmitting antenna orientation was used or 2) in a configuration which produced an exceedingly high, transient magnetic field. In both cases, recovery occurred after 2 ms, suggesting that - at a minimum - telemetry might be used once the projectile exits the EM launcher's barrel.

Several steps can be taken to avoid and/or mitigate both kinds of failures in future measurements. Using proper antenna polarization will help eliminate a failure due to the coupling of magnetic energy into the TM antenna. Failure due to excessive frequency deviations can be minimized by increasing the IF bandwidth to allow the receiver to track larger shifts in frequency. Additional improvements to this system in an EM environment include:

- Incorporating an isolator between the antenna and transmitter
- Using a highly frequency-selective antenna coupling to the transmitter (e.g., EM coupling)
- Employing a smaller, improved antenna design – e.g., one in which less of the railgun's off-axis magnetic field can couple to the antenna

Other areas that need to be addressed for the EM gun environment include:

- Technology dependent sensors (i.e., piezoelectric, piezoresistive, etc.)
- Signal conditioning and encoding circuits (digital & analog)
- Battery and power conditioning technologies
- Printed wiring board layout, component orientation, and board interconnect

Both in-bore and free flight measurement systems should be realizable for EM gun projectiles. The highly integrated components being produced by the U.S. Army's HSTSS program coupled with continued EM gun research and development activities will make telemetry a practical solution for on-board measurements in EM gun systems.

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